Scientific Productivity with X-ray All-Sky Monitors

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Science white paper prepared for

The Astronomy & Astrophysics Decadal Survey Committee

Panel on Stars & Stellar Evolution

1 Bright X-ray Sources and their Variability

We address the value of X-ray monitoring with a summary of the lessons learned from the *RXTE* All-Sky Monitor (ASM). We then describe goals and opportunities for progress in the next decade. The primary functions of X-ray monitors are (1) to find transients, so that they can be observed in detail, (2) to make light curves in different energy bands to support a variety of analysis tasks for the different classes of sources, and (3) to provide context for brief and specialized observations by other instruments.

The brightest celestial X-ray sources include many examples of accreting black holes (BHs), both stellar scale and supermassive (SMBH), and accreting neutron stars (NSs) in a variety of evolutionary conditions. These sources are used to address detailed questions concerning BH physical properties, the structure of NSs, the origin of relativistic jets in both binary systems and active galactic nuclei (AGN), specialized areas of cosmology (e.g., the warm-hot intergalactic medium), and the behavior of matter subjected to extreme temperatures, intense magnetic fields, or strong gravity. These topics are central to NASA's historical contributions to astrophysics, and they have remained cornerstones for science progress, e.g., in the priorities expressed in the Roadmap *"Beyond Einstein"*.

The X-ray sky is replete with variability. Many forefront themes in astrophysics depend on the response to windows of opportunity defined by unpredictable changes in flux or spectral characteristics. For example, it is believed that there are $\sim 10^8$ stellar-mass BHs in the Galaxy. However, our knowledge about these objects depends upon a very small number of mass-exchange binaries. X-ray eruptions lead to their discovery, and ensuing dynamical measurements of the companion star may indicate a compact-object that is too massive to be a NS. To date there are 18 known BHs in the Milky Way, plus 4 others in local galaxies (Remillard & McClintock 2006; Orosz et al. 2007; Prestwich et al. 2007). There are an additional $\sim$25 BH "candidates" in the Milky Way, based on the similarity of X-ray timing and spectral properties. Remarkably, 17 of the BH systems in the Milky Way and 21 of the BH candidates are X-ray transients (often recurrent). Random instrument pointings would usually find them in a quiescent state, which is a factor of 10^6 below the outburst maximum (McClintock & Remillard 2006). And even within a given outburst, there are state transitions associated with steady or impulsive types of relativistic jets (Fender 2006).

Many other types of X-ray sources are known to vary by a factor of 10 or more. Transients account for the majority of known NS accretors with low magnetic fields (so-called atoll and Z sources), as well as those with strong fields (i.e., classical X-ray pulsars). Furthermore, all 10 of the known X-ray millisecond pulsars are X-ray transients. These sources are an evolutionary bridge between accreting NS and millisecond radio pulsars, and the knowledge of their spin period is crucial for interpretations of X-ray burst oscillations (Watts et al. 2008), and for investigations of kHz quasi-periodic oscillations (e.g., Wijnands 2006).

Opportunities are also derived from X-ray variations in classes quite different from X-ray binaries. In the "blazar" (jet-dominated) type of AGN, major flares prompt multi-frequency observations that investigate the new ejections with coverage from radio to TeV gamma rays. We can further extend this discussion to include topics such as gamma ray bursts, tidal disruption events (i.e. stellar infall) into SMBHs in non-active galaxies, crustal-quake activity in magnetars, flares from stars with active coronae, and the poorly understood group of fast X-ray transients.

2 Statistics and Examples of X-ray Transients

The ASM archive provides light curves (1996-2009) for persistent sources and many transients discovered with *RXTE, BeppoSAX, INTEGRAL, and Swift*. For discussions of statistics, we adopt an X-ray flux threshold of 10 mCrab (or 2.4×10^{-10} erg cm^{-2} s^{-1} at 2-10 keV), which is about one thousand times fainter than the brightest source, Scorpius X-1. On average, our threshold is exceeded by $\sim$20 outbursts per year from 12 different sources, and $\sim$4 of these are seen as new discoveries for astronomy. Fig. 1 illustrates some of the activity of the X-ray sky during a roughly two year interval chosen at the center of the present decade. Each panel in Fig. 1 shows transients for different types of accreting binary systems.

Some noteworthy examples in our slice of the transients time-line are described as follows. The extremely bright recurrence of the dynamical BH binary GRO J1655-40 (Fig. 1, top panel, dark blue) provided new detections for the pair of high-frequency QPOs at 300 and 450 Hz (Homan et al. 2005), providing a strong message that these frequencies (first displayed in 1996) are an inherent signature of the accreting BH in that system. This source is one of the BHs for which a spin measurement ($a_* \sim 0.75$) has been derived from X-ray continuum analyses of observations in the thermal state (Shafee et al. 2006). In addition, observations with *Chandra* high-resolution gratings caught this source in a state where absorption features from an ionized wind were discovered and attributed to a strongly magnetized accretion disk (Miller et al. 2006).

The discovery of XTE J1701-462 (Fig. 1, middle panel, black) marked the first-ever appearance of a transient with the timing properties of a Z-type source (Homan et al. 2008). The large dynamic range in the luminosity of this X-ray transient provided a dramatic demonstration that the behavioral sequence – Cyg-like Z-source to Sco-like Z-source to atoll source – is a simple consequence of a decreasing mass accretion rate. Detailed spectral analyses of 866 pointed *RXTE* observations of XTE J1701-462 provided physical interpretations for each of the 3 branches of Z sources (Lin et al. 2009). The conclusions are now being evaluated for the persistent Z sources, and further tests are being conducted with data from other instruments.

Finally, the X-ray pulsar V0332+53 (bottom panel, green, maximum near 2005.0) is only the second case to show 3 or more cyclotron lines in

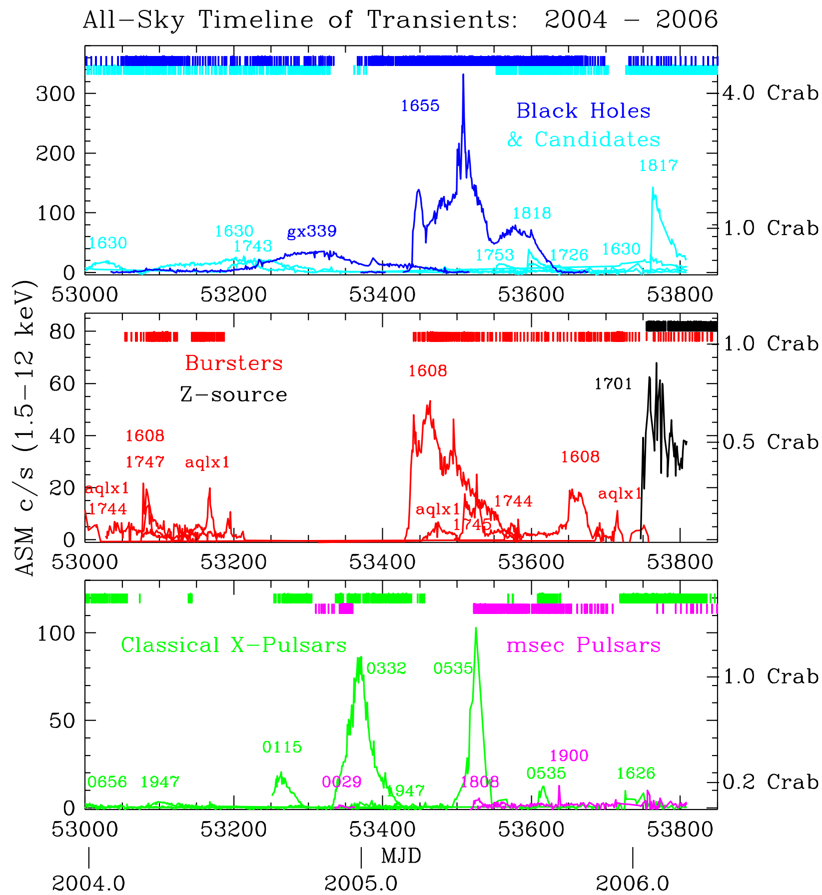

Figure 1: ASM light curves for selected types of transients, sampling 2004-2006. The top panel illustrates dynamical BHs (blue) and candidates (cyan). The middle panel shows NS binaries of atoll type (red) and the unique Z-type transient (black). The lower panel shows classical accretion-powered pulsars (green) and X-ray millisecond pulsars (magenta). Vertical ticks at the top of each panel show the times of *RXTE* pointed observations.

the X-ray spectrum (Pottschmidt et al. 2005). These lines determine the strength of the polar magnetic field to be 2.7×10^{12} G. Followup observations with *INTEGRAL* showed line shifts (to lower energy) that were linearly correlated with luminosity, allowing interpretation in terms of the height of a radiation-dominated shock above the NS surface (Tsygankov et al. 2006).

At a given moment, there are an average of 5 active transients that are brighter than 10 mCrab. At this level, the X-ray sky is still dominated by 66 persistent sources: 1 BH and 2 candidates in the Milky Way, 2 BHs in the LMC, 34 atoll and Z sources, 16 X-ray pulsars, 3 supernova remnants, 1 diffuse galactic component, 3 AGN, and 4 clusters of galaxies. Accreting NS and BH systems thus constitute the majority of the brightest X-ray sources. The overall science themes are interwoven between persistent sources and transients, and we note the following results. The catalogs of accreting

BHs, weakly magnetized NSs, and X-ray pulsars are now dominated by accumulated transients, rather than persistent sources, as noted in §1 (see Liu et al. 2006; 2007). Even among persistent X-ray binaries, flux variations by factors in the range 2 to 10 are common, and the observations at different luminosity are needed to test physical models of accretion in each type of binary and X-ray state (van der Klis 2006).

Some ground-based observatories also rely critically on X-ray light curves. The TeV observatories (VERITAS, HESS, Cangaroo, etc.) require long exposures and dark skies to detect microquasars and blazars, and they have successfully used the ASM data to choose targets in outburst (e.g., Krawczynski et al. 2004).

We conclude that the need for an all-sky monitor for bright X-ray sources is based on the following cornerstones: the value of transients, the importance of luminosity variations in X-ray sources, and the need to apply specialized instrumental capabilities to the science of accreting compact objects.

3 Goals for an Advanced Monitor, 2010-2020

Extensive use of ASM light curves and alert services in the past 13 years has clearly contributed to productivity in astrophysics. However, we have not fully absorbed these lessons. There is no mention of the critical role of wide-angle X-ray cameras in previous NASA roadmaps, and we are in serious danger of losing the capability to monitor the X-ray sky during the next decade. It would be an negligent to fly a mission such as the International X-ray Observatory without ensuring X-ray monitoring services in the same time frame.

In 2009, X-ray monitoring functions are still being carried out by the ASM (2-12 keV). There is also coverage in hard X-rays (10-100 keV) provided by INTEGRAL (ESA) and the Swift BAT (15-150 keV). All of these are "coded-aperture" cameras, and this remains the best imaging technique for wide-angle coverage with a design that is simple and cost-effective.

Currently, no future NASA missions will deploy wide-angle X-ray cameras, but two international missions will do so. The Japanese MAXI experiment is slotted for the Japanese Experiment Module on the ISS (2010?). It will sweep the sky once every 90 min with fan beams, yielding arcmin positions and sensitivity to 2 mCrab in 1 day. The Indian ASTROSAT Mission (2010?) includes a monitor designed after the *RXTE* ASM, providing 3 arcmin positions and sensitivity to 10-50 mCrab in 1 day for known sources.

We urge the NASA Decadal Survey Committee on Stars and Stellar Evolution to acknowledge the need for wide-angle X-ray cameras: (1) to provide alert and monitoring services for astrophysics programs seeking measurements of BHs, NS, and sources of jets, and (2) to gather primary spectral and timing data for a wide range of X-ray variations that enable detailed investigations in relativistic astrophysics.

Performance goals for wide-angle X-ray cameras and the primary rationale are as follows:

- 1 arcmin positions for new sources to facilitate identification and multi-frequency observations.
- minimum bandwidth of 2-15 keV to distinguish thermal and nonthermal spectral components.
- sensitivity to 1 mCrab (3σ; known sources) per day, to track transients into faint states and to monitor the brightest extragalactic sources.
- public archive for light curves and raw events (with sub-ms time resolution) to support diverse data analysis activities.

The avenues for improvement for an advanced instrument are simply the quantity and quality of the data products. One key parameter is the all-sky, average duty cycle (τ) that can be achieved in the instrument design. The ASM observes with $\tau \sim 0.02$, while the Wide Field Camera on *BeppoSAX* (Dutch-Italian; 1996-2002) operated with $\tau \sim 0.01$. The *Swift* Burst Alert Telescope (BAT), designed for gamma ray bursts (15-150 keV), now monitors the sky with $\tau \sim 0.10$. Such low coverage is insufficient to capture critical, infrequent events of exceptional interest. Additionally, the BAT responds only above 15 keV and is therefore incapable of observing the spectra of BH and NS accretion disks, and also NS boundary layer, which is crucial for understanding accretion physics.

Values of τ for selected instruments are shown versus photon energy in Fig. 2. Also shown are the duty cycles for special *RXTE* pointing campaigns on a single target. The most intensive such effort reached $\tau = 0.19$ for the 2002 outburst of the X-ray millisecond pulsar, SAX J1808-3658.

Argos-X – concept for an advanced all-sky X-ray observatory:
Fig. 2 also shows the design goal ($\tau = 0.5$) for *Argos-X*, proposed as a NASA SMEX in 2008. *Argos-X* would be the first observatory in any waveband to instantaneously view half the sky, while providing arcmin positions. The design consists of 25 cameras, each with field of view (FOV) of $40° \times 40°$, FWHM. The composite FOV covers the whole sky, except for a $60°$ circle intended as a solar exclusion zone. A simple operations plan calls for stationary pointing during observations, an equatorial orbit, and daily slews of $1°$ to maintain the solar axis. The average daily exposure would be 57 ks per source, reaching 1 mCrab sensitivity (4σ) for known sources.

Achieving a high value of τ would provide rapid advances in our understanding of cosmic explosions that occur on timescales of minutes to an hour, e.g. fast X-ray novae and GRB-related X-ray flashes (Heise & in 't Zand 2006). Such sky coverage also creates extraordinary synergy with other instruments: e.g. as the "eyes" for Advanced LIGO, as it "listens" for gravitational waves. There is also opportunity for partnership with wide-angle radio observatories under construction in each hemisphere: LOFAR (Netherlands) and the Murchison Widefield Array (US-Australia). The joint

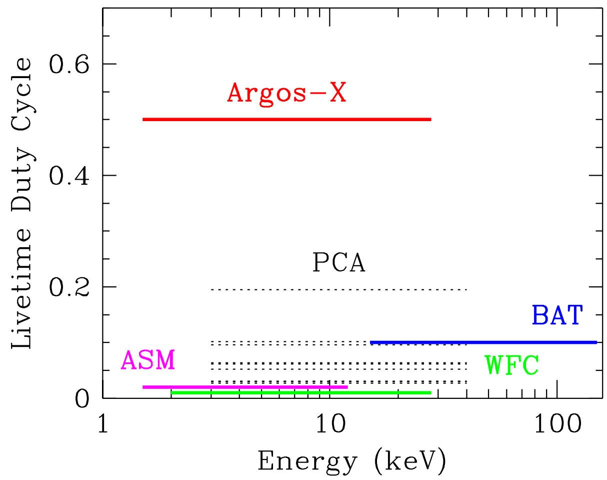

Figure 2: Average all-sky live-time fraction for wide-angle monitors (solid lines) or for the duty cycles of *RXTE* PCA pointings for noteworthy campaigns on a single source (dotted lines).

observations would provide a basis for solving the mysteries of relativistic jets (Fender 2006), where the primary obstacle has been the inability to gather data at those times when impulsive jets are launched. Productive partnerships would also be engaged with wide-angle optical facilities under construction: the Large Synoptic Survey Telescope (LSST) and the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS).

The quality of primary data products from wide-angle X-ray cameras further depends on the choice of the detector. Technology plays a large role in defining options. Si pixel detectors are already available with large pixel size (e.g. 2.5 mm), fast time-tagging capability, broad sensitivity range (e.g. 1-30 keV for 0.5 mm pixel depth), and good energy resolution (e.g. 600 eV with current designs for low-power ASICs). Further improvements are expected in the next few years.

Compared to the ASM, an advanced X-ray monitor could achieve tenfold improvements in sensitivity and position resolution, while observing with a broader energy range and τ increased by a factor of 25. Si detectors can produce data products that rival the quality of current pointed instruments. For example, for bright sources it would be possible to do the coded-mask spatial deconvolution every 3 ks, with 128 spectral channels covering 1.5-30 keV, thereby providing outstanding capabilities, e.g., for observing relativistic Fe lines in BH sources. The primary data and followup observations would address the following science goals:

- Find BHs in the Galaxy and conduct spectral analyses of the continuum and Fe line to constrain mass and spin.
- Capture state transitions in X-ray binaries to determine the nature of non-thermal X-ray states.

- Capture accretion disk changes that cause impulsive relativistic jets in Galactic microquasars.
- Measure Fe line variations with luminosity or state to help prepare for the International X-ray Observatory.
- Measure the locations, spin, magnetic fields, and radiation properties of NS in the Milky Way.
- Use routine exposure times of 10^7 s to determine binary periods and to study X-ray bursts and superbursts.
- Survey the local universe for SMBHs that are quiescent (via stellar infall events) or obscured from view (via detections at 5–20 keV).
- Measure break frequencies in the power spectra of active galaxies and relate these to the masses of their SMBHs.
- Measure new ejections in the jets from "blazar" type AGN.
- Provide time-critical information to other space missions and ground-based observatories in order to increase their productivity.
- Survey gamma ray bursts in the X-ray band and use them to support efforts to detect gravitational waves with Advanced LIGO.

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